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Continental atmospheric circulation over Europe during the Little Ice Age inferred from grape harvest dates

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Abstract

Estimates of climate conditions before the 19th century are based on proxy data reconstructions or sparse meteorological measurements. The reconstruction of the atmospheric circulation that prevailed during the European Little Ice Age (∼1500–1850) has fostered many efforts. This study illustrates a methodology combining historical proxies and modern data sets to obtain detailed information on the atmospheric circulation that prevailed over the North Atlantic region during the Little Ice Age. We use reconstructions of temperature gradients over France based on grape harvest dates to infer the atmospheric circulation. We find that blocking situations were more likely in summer, inducing a continental atmospheric flow. This study advocates that the reconstructions of the past atmospheric circulation should take this regime into account.

1 Introduction

The climate anomaly of the Little Ice Age (LIA) affected most of European population between 1500 and 1850. This period underwent a few multidecadal episodes of anomalously cold temperatures that jeopardized crops and public health (Le Roy Ladurie, 1971). There have been several attempts to estimate the features of the atmospheric circulation during that period (Jacobeit et al., 2003; Jones et al., 1999; Luterbacher et al., 2000, 2002; Slonosky et al., 2001; Trouet et al., 2009; Briffa et al., 1986, 1987). Some studies have relied on the relationship between the atmospheric circulation and surface temperature or other proxy records (Briffa et al., 1986; Souriau and Yiou, 2001; Luterbacher et al., 1999, 2000). A major challenge to investigate this period is the rarity of reliable meteorological measurements before the 18th century. Historical archives provide direct testimonies of such events and their impacts on society and the environment (Brazdil et al., 2005; Kuttel et al., 2010). An important task is then to translate them into quantitative climate variables.

In this paper, we use a new extensive database of historical grapevine harvest dates (GHD) covering France and Switzerland, during the past centuries, to reconstruct atmospheric conditions during the LIA. This dataset was built by a team of climatologists, historians, agronomists and ecophysiologists (see list of co-authors). Important contributions of this new database are its spatial coverage and its position in a socio-historical context (Garnier et al., 2010) that allow access to information about regional climate.

2 Data and method

2.1 Historical grape harvest dates

We used eight original datasets of west-European grapevine harvest dates (GHD), including eight in France (Bordeaux, Loire Valley, Rhone Valley, Ile-de-France, Alsace, Burgundy and Jura) and one in Switzerland (Lac Léman). Each series was constructed from an ensemble of harvest dates recorded at different sites. When documentary sources from several vine growers were available for the same period, grapevine harvest dates were obtained as the median date among all available standardized dates including a reference series (Table 1 in Supplement) following the methodology developed by Chuine et al. (2004). The number of available GHD observations for each region is reported in Fig. 1. For each GHD series, a precise identification of the grapevine varieties cultivated was carried out based on the expertise and grapevine varieties database of the INRA “Domaine de Vassal” (http://bioweb.ensam.inra.fr/collections_vigne/), and on old literature available in the European and French digital libraries (Europeana; URL: http://www.europeana.eu; Gallica; URL: http://www.gallica.fr) and Google Books (URL: http://books.google.fr) (Guyot, 1868a, b, c; Jullien and Jullien, 1866; Odart, 1845; Galet, 1956, 2004, 2006). Datasets were classified according to regional and historical agriculture criteria (Jullien and Jullien, 1866; Guyot, 1868a, b, c; Odart, 1845) such as the geographical structure of the vineyard, the viticultural practices and the varieties cultivated. As García de Cortázar-Atauri et al. (2010) showed, variety and agricultural information are particularly important for the accuracy of climate reconstructions using grapevine harvest dates. For example, Eastern series were separated into three series: Jura, Burgundy and Switzerland, because even if these regions are not very far apart (within 75 km), there are important differences in the cultivated varieties (Table 1 in Supplement). A complete and detailed description of the grape harvest date dataset used in this study can be found in a companion paper (Daux et al., 2011).

For calibration and comparison purposes, we used temperature observations over the 20th century from the ECA&D database (Klein-Tank et al., 2002) for Switzerland and from Météo-France (O. Mestre, personal communication, 2009) for France. The French temperature data were homogenized by a procedure of (Caussinus and Mestre, 2004) and breakpoints could be documented (S. Jourdain and O. Mestre, personal communication, 2009).

2.2 Phenology model

To construct and validate the process-based phenological models used to reconstruct temperature anomalies from GHDs, an important dataset of contemporary phenological observations of grapevine was used. This database contains more than 2000 phenological observations for each main phenological stage (budbreak, flowering, veraison) coming from different places in France, Switzerland and Italy and for around 100 grapevine varieties (Parker et al., 2011).

The process-based phenological model used was presented in García de Cortázar-Atauri et al. (2010). The model describes two independent phases: the first phase calculates veraison date; and the second one goes from veraison to harvest date.

The first phase is modeled using the model of Wang and Engel (1998) which has four parameters: a minimum, optimum and maximum temperature (T_{min},T_{opt},T_{max}) and a threshold of cumulated temperature actions ($F*$) (dimensionless). The date of veraison is such that:

$$F* = \sum_{t=t_0}^{t_{\text{veraison}}} \mathrm{RF}(T_t),$$
$$RF(T_t) = \begin{cases} \frac{2(T_t - T_{\min})^{\alpha}(T_{\text{opt}} - T_{\min})^{\alpha} - (T_t - T_{\min})^{2\alpha}}{(T_{\text{opt}} - T_{\min})^{2\alpha}}, \text{ if } T_{\min} \leq T_t \leq T_{\max}, \\ 0, \text{ if } T_t < T_{\min} \text{ or } T_t > T_{\max}. \end{cases} \tag{1}$$

In Eq. (1), the parameter α is:

$$\alpha = \frac{\log 2}{\log\left[\frac{(T_{\max} - T_{\min})}{(T_{\text{opt}} - T_{\min})}\right]}. \tag{2}$$

The date t_0 is the day when rates of forcing (RF) accumulation starts and was optimized using all veraison dates available for grapevine in the database. Its estimate was 15 March, which is close to values found in previous studies on grapevine phenology (Williams et al., 1985; Nendel, 2009; Parker et al., 2011) and it was fixed the same for all varieties. Cardinal temperatures $T_{\min}$ and $T_{\max}$ were fixed at 0° C and 40° C respectively (Champagnol, 1984; Jones, 2003) and T_{opt} and $F*$ were optimized for each variety respectively. Table 2 in Supplement provides parameters and statistical indicators of the model accuracy (efficiency, confidence intervals and root mean square error) for each variety identified in each region.

The veraison-harvest period was described by a constant number of days (N, Table 3 in Supplement). Each value was related to the vineyard (varieties, style of wine), the agricultural practices and the crop state (water, carbon and nitrogen balances) (Jones, 2003; Holt et al., 2008; García de Cortázar-Atauri et al., 2010). In this study, this constant and the possible error due to cultural practices and climate conditions, were obtained using combined information of two different sources, our phenological database, and a mechanistic generic crop model, STICS (http://www.avignon.inra.fr/agroclim_stics) (Brisson et al., 2002, 2003, 2009), adapted to grapevine (García de

Cortázar-Atauri, 2006). The STICS crop model is a daily time-step model that simulates crop growth, soil water and nitrogen balances driven by daily climatic data. The annual development of grapevine in the model is described by the main phenological stages (Jones, 2003; García de Cortázar-Atauri et al., 2009b). To simulate biomass growth, the STICS model uses nitrogen and carbon reserves of grapevine and takes into account competition between vegetative and reproductive organs. The fruit growth is described by the dynamics of dry matter accumulation and water content (García de Cortázar-Atauri et al., 2009a; Brisson et al., 2009). To assess the uncertainty generated by past technical practices and not only by thermal climate variables, a range of inputs was provided to the STICS crop model: representative regional soil characteristics (field capacity, wilting point and bulk density) (García de Cortázar-Atauri, 2006; Brisson et al., 2009) and STICS crop soils database: http://www.avignon.inra.fr/agroclim_stics), historical technical conditions described in old references (plant density, row orientation, canopy geometry, fruit load, nitrogen fertilization, trimming date) (Guyot, 1868a, b, c; Bidet, 1759b, c; de Serres, 1600; Jullien and Jullien, 1866), quality description and harvest decision (based on sugar content reached at harvest) (de Serres, 1600; Estienne and Liebault, 1589; Chaptal, 1801; de Herrera and Real Sociedad Económica Matritense, 1818; Gay-Lussac, 1828; Laudier, 1852; Maumene, 1858; Gautier, 1891), variety information (Odart, 1845; Rendu, 1857; Jullien and Jullien, 1866; Galet, 1956, 2004, 2006) and daily weather data (maximum and minimum temperatures, rainfall, radiation, wind and humidity) (INRA Agroclim database). Their analysis provided an estimation of the uncertainty on grape harvest date linked to cultural practices and non thermal climate variables (Table 3 in Suplement) (García de Cortázar-Atauri et al., 2010).

The daily mean temperature of the closest weather station (within 5 km radius) was used for the parameterization of the process-based phenological model. Mean temperature was calculated as the arithmetic mean between the daily minimal and maximal temperatures.

The methodology developed by Chuine et al. (2004) was used to reconstruct temperature anomalies from the nine composite series. Temperature anomalies were determined with respect to a reference temperature (15 March–August mean temperature of the 1960–1989 periods) by inverting the process-based phenological models. The inversion consisted in fitting the average anomaly temperature that would provide the observed past harvest date with the phenological model. Temperature anomalies correspond to the 15 March to 31 August period and were calculated for all the varieties that have been grown during the period investigated in each region. The final temperature anomaly of a region was calculated as the arithmetic mean of all anomalies obtained with the different varieties of this region.

3 Results

3.1 Grape harvest dates and temperature reconstructions

From the set of nine reconstructed temperature anomalies, we selected four groups of vineyards corresponding to the four cardinal regions of France (Bordeaux and Loire Valley for the West, Burgundy, Jura and Switzerland for the East, Rhone Valley for the South and Ile-de-France and Alsace for the North). These four regions were chosen to estimate meridional and zonal temperature gradients.

We chose to study gradients of temperature (rather than gradients of temperature anomalies). This does not alter the inferred dynamics and provides a better physical intuition on the thermal differences. The temperatures series for each cardinal region are reconstructed by adding the mean temperature anomaly of the region to the average temperature of the 15 March–August period over 1960–1990 of a reference weather station. The reference weather station for the North was Paris, Orange for the South, Bordeaux for the West and Dijon for the East. Hence the temperature gradients are obtained from the temperature reconstructions.

The temperature anomaly reconstructions and observations are shown in Fig. 2. In each cardinal region, there is a good agreement among the temperature anomalies

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reconstructed in the different vineyards over the 1950–2000 period, with correlation coefficients r always exceeding 0.76 (p values $< 10^{-11}$). The correlation coefficients still exceed 0.67 (p values $< 10^{-13}$) over 1900–1950, except in the south of France, where $r = 0.57$ (p values $< 10^{-9}$). GHD-based temperature anomaly reconstructions (Fig. 2) generally yield interdecadal fluctuations that are consistent with estimates from other proxy records (Guiot et al., 2005; Maurer et al., 2009; Meier et al., 2007).

The grapevine varieties vary from one region to another as a response to local climate and soil characteristics (Van Leeuwen and Seguin, 2006). The timing of grape harvests has been regulated and scheduled on a local level, generally by groups of experts (mainly winegrowers) from the area (de La Poix de Fréminville, 1758; Pocquet de Livonnière, 1733; Salvaing de Boissieu, 1664). Even if agricultural practices from one region could cross its borders, each region shows specific particularities (Guyot, 1868d). Hence, it is remarkable that Rhone valley harvest data series has a similar behavior as the Languedoc dataset (data not shown, Daux et al., 2011) showing a decreasing trend in reconstructed temperatures between 1600 and 1700 unlike those at the other cardinal regions. The analysis of various agriculture-viticulture books edited before the 19th century does not show major differences, nor significant revolutions in vineyard management for the period studied in those vineyards (Alonso de Herrera, 1513; Estienne and Libeault, 1589; de Serres, 1600; Bidet, 1759a). Moreover the decreasing temperature trend in southern France between 1600 and 1700 is consistent with the result of other studies in the same region (Guiot et al., 2005; Maurer et al., 2009). The discrepancy between the reconstructed and observed temperature anomalies in Southern France in 1880-1920 is certainly due to a low number of available GHD series during this period in this area (Fig. 1 Supplement), because of several particular events such as the disappearance of the “bans de vendanges”, the vineyard reconstruction after phylloxera epidemics from 1867 to 1898.(Direction Departementale de l’Agriculture (DDA) and Service Central des Enquêtes et Études Statistiques (SCEES), 1983; Branas, 1974), and the 1910 mildiou outbreak.

3.2 Temperature gradient reconstructions

We computed the differences between temperature reconstructions from the North and the South, and from the West and the East. As specified in Fig. 2, the northern region includes Ile-de-France and Alsace, the southern region include Rhône Valley, the western region includes Bordeaux and Val de Loire, and the eastern region includes Burgundy, Jura and Switzerland. Those differences approximate North-South and West-East temperature gradients in France (Fig. 3). We determined confidence intervals over non-overlapping periods of 30 yr by computing 10th and 90th percentiles, bracketing the local median. Those confidence intervals allow estimating the significance of interdecadal changes in the temperature gradient.

The reconstructed gradients can be compared to differences of instrumental temperature anomalies. The correlations are rather weak ($r = 0.21$, p-value $= 0.13$ for N-S gradients, and $r = 0.45$, p-value $= 10^{-3}$ for W-E gradients), but the means ($m = -2.5\,^{\circ}\mathrm{C}$ for N-S and $\sim 1.9\,^{\circ}\mathrm{C}$ for W-E) and standard deviations (standard deviation $\sim 0.5\,^{\circ}\mathrm{C}$ for N-S and $\sim 0.4\,^{\circ}\mathrm{C}$ for W-E) for 1950–2000 are both correctly reproduced (p-value $= 0.01$ for a two-sided Kolmogorov-Smirnov test).

Divergences between the observed and reconstructed N-S gradient appear before 1960. The discrepancy between 1900 and 1920 is probably due to the already mentioned lower number of GHD series during this period in Southern vineyards. Our reconstruction yields variations for the North-South (N-S) temperature gradient, with values ranging from $-4\,^{\circ}\mathrm{C}$ to $0\,^{\circ}\mathrm{C}$. The gradient shows a long period without large breakpoints, between $-2\,^{\circ}\mathrm{C}$ and $-1\,^{\circ}\mathrm{C}$ on 30 yr-average, from 1700 to 1850, followed by an important decreasing trend up to 1880. It yields large variations at the end of the 17th century (from -4 to $-1\,^{\circ}\mathrm{C}$) and a decreasing trend since the 1940s. This gradient is minimal at present, with an average of approx. $-3.2\,^{\circ}\mathrm{C}$ between 1980 and 2006 The West-East (W-E) temperature gradient does not have such clear-cut variations, and its amplitude is weaker than the North-South gradient. It is, on average, a little larger during the 19th century and shows oscillations with an amplitude of $\sim 2\,^{\circ}\mathrm{C}$ during the 20th century. Thus, rather than discussing year-to-year variations of temperature gradients that are not meaningful, we focus on persistent multi-decadal states of the reconstructed gradients, especially before the 20th century.

3.3 Atmospheric flow inference

The methodology to assess the features of the atmospheric flow is based on the temperature gradient reconstructions. The relation between the atmospheric circulation and surface conditions has been investigated by many authors (Luterbacher et al., 1999; Folland et al., 2009; Souriau and Yiou, 2001; Trouet et al., 2009). Indices of circulation, such as the North Atlantic Oscillation index, have been used to establish such dependence and it has been argued that the atmospheric circulation can be inferred from surface temperature or precipitation observations through such indices (Briffa et al., 1987). Here, we exploit the relation between present temperature patterns and large-scale circulation over the North Atlantic.

The reconstructed N-S temperature difference can be above −2 °C (i.e. flat gradient). From recent observed temperature (between 1950 and 2007), we determined the days for which this value is exceeded during the Mid-March to August period, which corresponds to the period of our reconstructed temperature. We then computed composite sea-level pressure (SLP) from the National Centers for Environmental Prediction (NCEP) reanalysis data (Kalnay et al., 1996) to obtain the prevailing atmospheric circulation for high North-South temperature anomaly gradients. When steep N-S gradients ($< -3\,^{\circ}$C) occur, e.g. between 1950 and 2000, the circulation yields a zonal flow pattern which is consistent with a frequent positive phase of the North Atlantic Oscillation (Fig. 4a) and strong thermal wind (Marshall and Plumb, 2008). When the N-S gradient is weaker ($> -2\,^{\circ}$C), the atmospheric circulation corresponds to a blocking pattern (Rex, 1950) (Fig. 4b, c).

We checked from the NCEP reanalysis SLP (Kalnay et al., 1996) that the circulation patterns corresponding to a high temperature gradient are mutually consistent, and correspond to a blocking situation with an anticyclonic pattern over Western Europe. This was done by computing the spatial correlation between the circulation pattern of each day (between 1948 and 2004) with a temperature gradient above −2 °C and the composite circulation pattern and verifying that the correlations are positive and significant (Fig. 5). The box-and-whisker plot in Fig. 5 shows that more than 70 % of the days with a temperature gradient above 2 °C have a positive correlation with the composite SLP pattern corresponding to this temperature gradient (shown in Fig. 4b). Moreover, 60 % of those days have a significant correlation with the composite SLP pattern. This shows that this composite circulation pattern has a meaningful signature on the temperature gradient. The moderate score is explained by the large intra-seasonal atmospheric variability (Cassou et al., 2005; Philipp et al., 2007). This correlation is accentuated if the constraint of a large West-East gradient is added.

We verified that the pattern is coherent with atmospheric circulation estimates by comparing the results with the EMULATE gridded sea-level pressure (SLP) dataset (Ansell et al., 2006) over the 1890–1910 period, during which the N-S temperature gradient during the warm season is low (Fig. 4d). The EMULATE dataset shows an anticyclonic pattern over Western Europe, albeit weaker than the one inferred from the reconstructions in Fig. 4b–c. Hence we were able to infer a dominating atmospheric circulation pattern corresponding to high and low values of temperature gradients over the cardinal regions of France (Fig. 4). This result is consistent with reconstructions that infer more continental circulation during the Little Ice Age (Jacobeit et al., 2003; Folland et al., 2009). The order of magnitude of the SLP pattern reconstruction is also broadly consistent with other estimates (Kuettel et al., 2010; Luterbacher et al., 2002) for the 18th century.

This synoptic weather pattern lasts from a few days to several weeks (Michelangeli and Vautard, 1998). It does not exclude that zonal atmospheric patterns, such as the phases of the North Atlantic Oscillation, occur and bring moist air to Western Europe. Hence we insist on the caveat that our inferred SLP pattern is the one that is most likely given a seasonal temperature gradient reconstruction. This inference cannot be extended to subseasonal variability (Michelangeli et al., 1995; Corti et al., 1999) in a trivial way.

4 Discussion and conclusion

This paper has explored the potential for grape harvest dates to reconstruct spatial information of past climate variability. Such data contain a fine network that gives access to regional climate variations. The temperature reconstructions show shifts in temperature North-South gradients. Such shifts are identified on multi-decadal periods. They can have a mean amplitude as high as 1 °C. We found no evidence in historical agronomical documents in wine growing practice changes in those regions and hence assumed that their origin is a climate change. This trend is also coherent with other independent proxy reconstructions (Guiot et al., 2005).

We proposed a methodology to reconstruct mean atmospheric circulation patterns. This reconstruction is based on the present observation that high and low North-South temperature gradients are connected to synoptic atmospheric patterns. Hence we were able to infer an atmospheric circulation patterns that is compatible with high and low values of North-South temperature gradients. This approach is similar to the method of analogues (Vautard and Yiou, 2009), and we also propose a test of the significance of the inferred circulation. The caveat of this approach is that the circulation inference is a composite that is only valid for multi-decadal period for which the sample size of high (or low) temperature gradient values are observed.

We find that a likely atmospheric pattern that prevailed during periods of relatively “flat” temperature gradient, especially between 1700 and 1850 AD is a blocking that brings continental flow over Western Europe. This finding advocates for a description of atmospheric variability that goes beyond the phases of the North Atlantic Oscillation and takes weather regimes into account (Michelangeli et al., 1995; Yiou and Nogaj, 2004; Yiou et al., 2008).

Those results will be used to constrain the local scales of climate simulations of the last millennium.

Finally, our results emphasize the importance of interdisciplinary investigations to assess the sources of uncertainties in the climate reconstructions.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/7/3023/2011/cpd-7-3023-2011-supplement.pdf.

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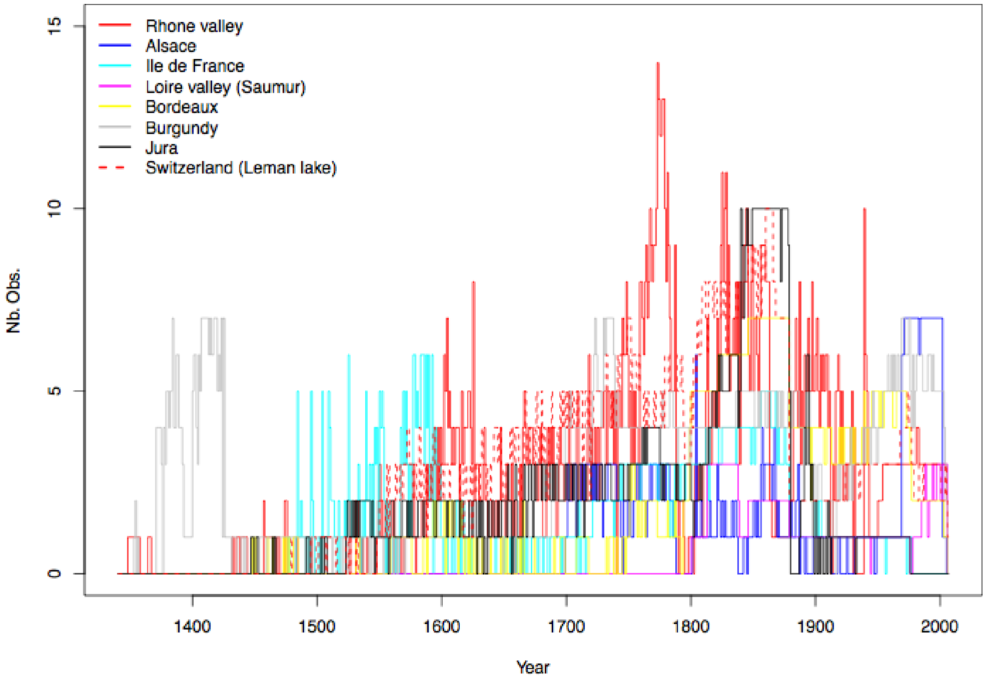

Fig. 1. Number of observations for each viticulture region and for each year.

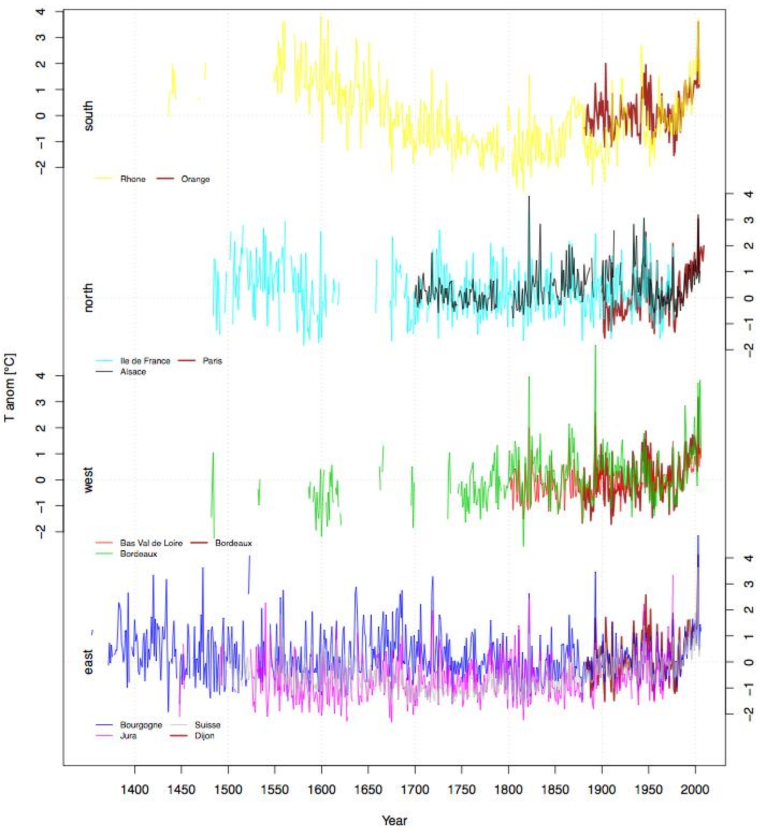

Fig. 2. Reconstructed temperature anomalies of the mid-March to August temperature deduced from GHD in four French regions (South, North, West and East: thin lines). Heavy brown lines indicate observed temperature anomalies from the ECA&D database (Klein-Tank et al., 2002) and homogenized data from Météo-France (O. Mestre, personal communication, 2009) for Orange, Paris, Bordeaux and Dijon cities.

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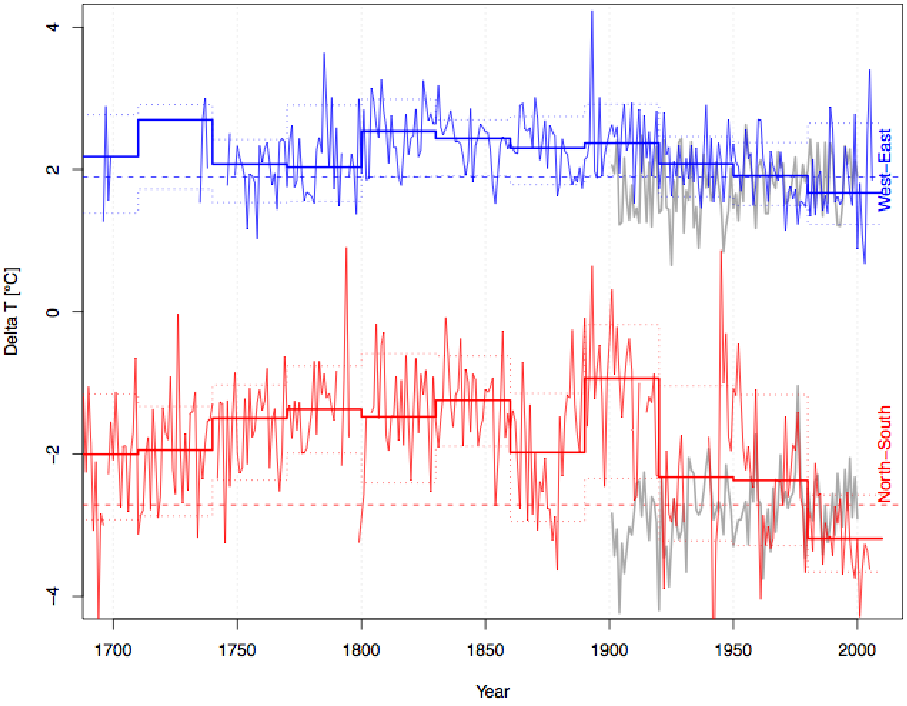

Fig. 3. Differences between North and South (N-S: red line), and West and East (W-E: blue line) reconstructions of mid-March-August temperatures. Colored (red and blue) step lines correspond to 10th, median and 90th quantiles of variations over non overlapping windows of 30 yr. Grey lines refer to the April to August temperature differences between Bordeaux and Dijon (W-E), and Paris and Orange (N-S). The horizontal dotted lines represent the mean of the observed temperature gradients.

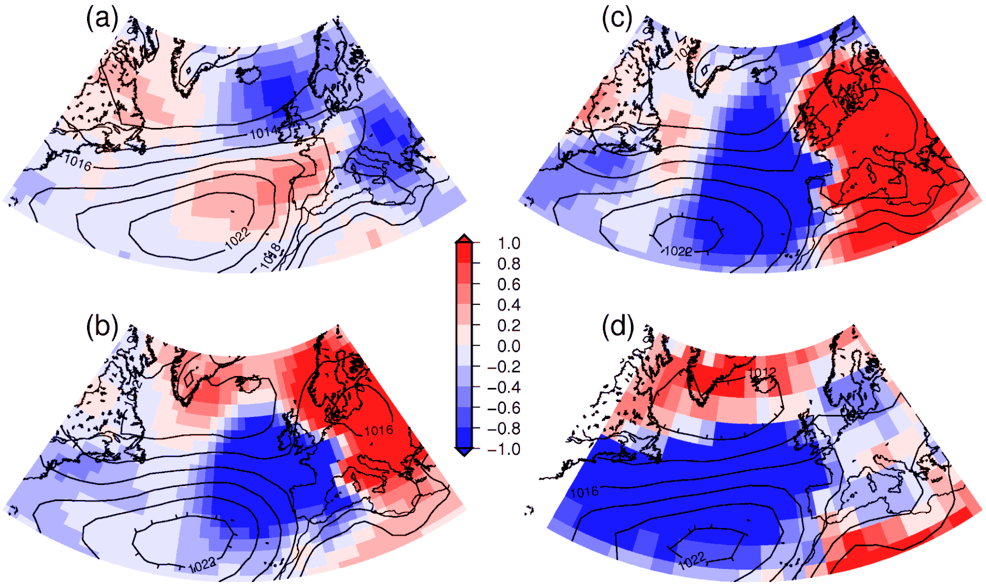

Fig. 4. **(a–c)**: inferred sea-level pressure (SLP) patterns from reconstructed temperature anomaly gradients. Panel **(a)**: large N-S temperature anomaly gradients; **(b)** small N-S temperature anomaly gradients; **(c)** small N-S and large W-E temperature gradients. Panel **(d)** average SLP for the 1890–1910 period from the EMULATE dataset (Ansell et al., 2006). Isoline contours indicate SLP patterns, with 2hPa increments. Colors indicate SLP anomalies (in hPa).

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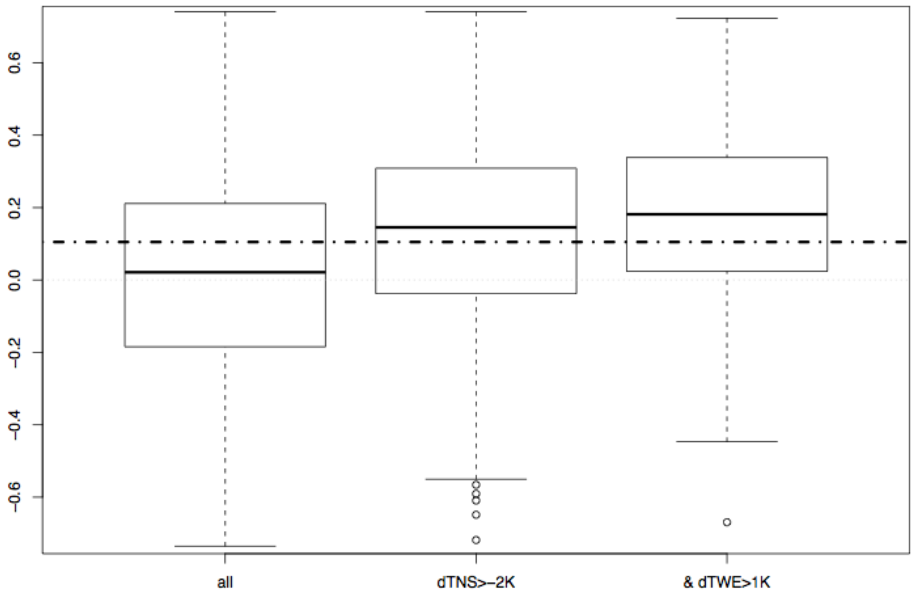

Fig. 5. Box-and-whisker plots of spatial correlations between the composite pattern of sea-level pressure (from NCEP reanalysis) obtained for days of high North-South temperature difference between April and August: all days (“All”), days with N-S temperature differences larger than −2 K (“dTNS> −1.5 K”), days with N-S temperature differences larger than −2 K and W-E temperature differences larger than 1 K (“& dTWE>1 K”). The dash-dotted horizontal line is the correlation has a p-value under 10^{-3}.

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